THE MECHANICAL SPINDLE: A REPLICA OF THE MAMMALIAN MUSCLE SPINDLE

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Abstract—**The goal of the recently initiated anthroform arm project is to understand the manipulation capabilities of the human arm through the development of a dynamically accurate replica arm. One key element is the mammalian muscle spindle responsible for position and velocity feedback. This paper describes the important spindle features that we are attempting to copy, as well as the mechanical and software aspects of our first prototype. The model and prototype include active modulation of spindles' non-linear response which models the gamma efference. The sensor that was developed can also be used for other applications, and shows unique adaptive properties.**

I. Introduction

Traditionally, designs attempting to replicate the human arm have focused on manipulator kinematics, and neglected controller designs [1]. Others have emphazied neural network control without attention to correct biomechanical modeling[2]. The goal of the Anthroform Biorobotic Arm project has been to build an anthropomorphic robot such that both the manipulator and its controller are based on current knowledge of human biomechanics and neurophysiology respectively.

Our system consists of two sub-projects: the Anthroform Arm Manipulator and the Anthroform Neural Controller. The manipulator is a biomechanically accurate, actuated human arm replica developed by Professor Jack Winters of Catholic University. It utilizes pneumatic Mc Kibben artificial muscles, fiberglass bones molded from human bones, and artificial joints developed for total replacement surgery [3]. The controller for this arm simulates the activity of spinal neuron pools through a combination of specialized hardware and software [4]. Together, the Manipulator and Neural Controller will provide a versatile testbed for studying spinal reflex control.

The actuated human arm replica needs position sensors. The research presented here describes a prototype active measurement system which is designed to function as closely as possible to the human spindle. The mechanical spindle will be placed in parallel with the Mc Kibben actuators.

II. Neurophysiology Background

Figure 1 shows a muscle spindle [5] and a typical response, calculated from Hasan's spindle model [6]. In vivo, the spindle's sensitivity to velocity can be altered by activating the Gamma dynamic inputs. The sensitivity to position is altered with Gamma static inputs. The outputs of the spindle (a function of the stretch of the central part of the spindle) use two main types of nerve fibers, classified according to their conduction velocity. Ia fibers are the most numerous [7].

It has been shown that the muscle spindle is responsible for position (and velocity) feedback in the control of posture. Other receptors (such as Golgi tendon organs, transducing muscle force and pressure sensors in the joints) play an important but secondary role[8].

A spindle constitutes an active sensor, whose properties are altered by the CNS, according to its needs. For example, when a movement is being learned, Gamma dynamic activity is high in the muscles used. This activity decreases when the trajectories have been learned[9].

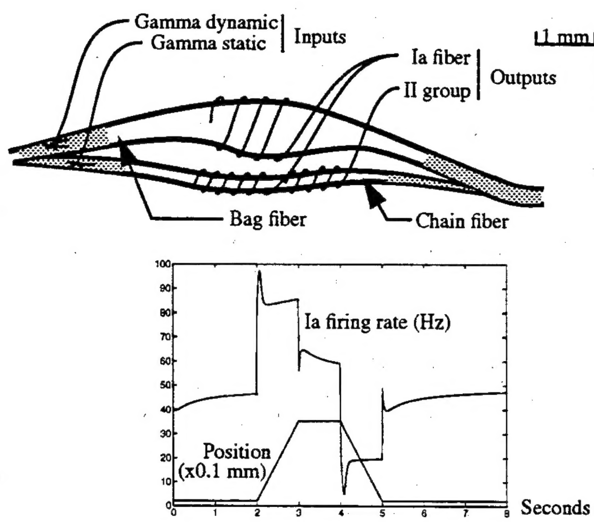

Fig. 1. A Muscle spindle and one simulated response.

III. The Mechanical Spindle

The problem with the mechanical version is its actuator. The closest alternatives to muscle fibers are pneumatic Mc Kibben actuators which replicate the main muscles of the arm. Using them in the spindle would have required doubling the number of electro-valves, and of air tubes to the arm. This was found to be cumbersome. Electrical direct-drive options did not provide enough force (up to 1N), so a DC motor-leadscrew assembly was used.

Figure 2 shows the mechanical copy of the muscle spindle: an aluminium tube holds a non-linear force sensor in series with a spring, a leadscrew mechanism, a DC motor and a VCO circuit which is used to convert the output of the strain gauges. The complete assembly has a 1 cm diameter. The motor is driven by Pulse Width Modulation, and its feedback (θ) is obtained

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from an optical encoder using quadrature signals. In this way, all the signals exchanged between the spindle and the processor are immune to noise because they are either frequency encoded or binary. A controller drives the motor so that it simulates the gamma muscle (intrafusal) fiber. Finally, the Ia response software module matches the response of the real spindle.

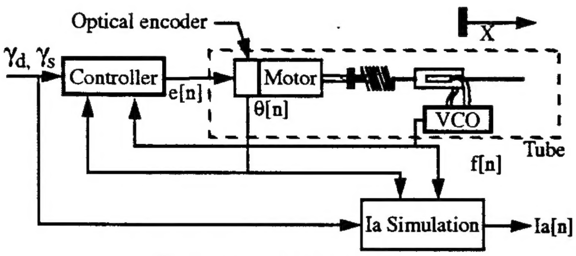

Fig.2. Actuated Spindle Setup.

IV. The Interface Card and the Spinal Cord

A set of custom processor cards based on the TMS320C30 Digital Signal Processor (DSP) and interconnected with a special bus (NB Bus [4]) is responsible for executing neural processing functions, handling sensor input and motor output, and communicating with a host.

An I/O daughter card was developed to drive up to four mechanical spindles. Each "channel" is composed of a PWM output, an optical encoder input, and a frequency signal decoder. The latter (when associated with the VCO inside the spindle) constitutes a A/D channel with gain and offset adjustable by software, and a high immunity to noise.

The control law for the spindle motor is a very high gain P.D. with adjustable coefficients. The selected spindle motor is able to position the leadscrew along its travel (30 mm) in less than 0.5 seconds.

The first controller and Ia simulator laws to be implemented will be:

$$e[n] = M * \mathrm{SIGN}\big(f[n - g(\gamma_d[n])] - f_0 + \alpha\,(f[n - g(\gamma_d[n])] - f[n - g(\gamma_d[n]) - 1])\big)$$

$$Ia[n] = (\theta[n] - \theta_0) . (\gamma_s[n] + A) . B + (f[n] - f_0) . (\gamma_d[n] + C) . D$$

where: Ia[n] are the Ia outputs; $\gamma_s[n]$ and $\gamma_d[n]$ are the static and dynamic Gamma inputs; θ[n] are the optical encoder positions, f[n] are strain gauge measurements; A, B, C and D are model parameters; M is maximum motor torque; α is a coefficient that is updated for maximum controller performance.

$g(\gamma_d[n])$ introduces a delay in the controller so that f[n] reflects dX/dt;

The parameters are adjusted to fit experimental data and outputs from current models [6][10][11][12][13] (when a relevant experiment is not found).

V. Conclusion and Future Work

The mechanical muscle spindle introduces a new kind of sensor, original in two respects: it is active, and therefore capable of adjusting itself through a variable bias on the non-linear strain gauge; and it also uses two sensors in series, therefore giving it enhanced resolution. In the current design, the optical encoder gives a linear resolution of 16 microns, the strain gauges give 3 to 9 microns (their response is not linear). Inside the range of the strain gauges (1.5 mm), the resolution of the spindle is 3 to 9 microns. The dual, independent sensor assembly permits velocity estimation. The motor/leadscrew can be used in conjunction with the non-linear sensing element to vary the natural frequency of the sensor for adjustable frequency selective response.

By trying to copy the human arm, we have generated a new technology for sensors. The prototype is complete, and almost ready to be tested.

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